NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 404

THE EFFECT OF INCREASED CARBURETOR PRESSURE ON ENGINE PERFORMANCE AT SEVERAL COMPRESSION RATIOS

By OSCAR W. SCHEY and VERN G. ROLLIN

1931

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s$^2 = 32.1740$ ft./sec.^{2}

m, Mass $= \frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 760 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3 = 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $= \frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of *c. p.* from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute. (Measured from zero lift position.)

γ Flight path angle.

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By OSCAR W. SCHEY and VERN G. ROLLIN
Langley Memorial Aeronautical Laboratory

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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By Oscar W. Schey and Vern G. Rollin

SUMMARY

The object of this investigation was to determine the effect of increasing the carburetor pressures from 30 to 40 inches of mercury, at compression ratios from 3.5 to 7.5, on the power, on the maximum cylinder pressures, on the fuel consumption, and on the other performance characteristics of an engine. The tests were conducted on the N. A. C. A. single-cylinder universal test engine by the staff of the National Advisory Committee for Aeronautics. A Roots-type aircraft-engine supercharger was used to maintain the desired carburetor pressure.

The results of these tests show: That the decrease in brake thermal efficiency with boosting is negligible; that the power increases with boosting much more than the losses to the cooling water increase; that a large increase in power can be obtained with comparatively small increase in maximum cylinder pressures; and that it is advisable to supercharge an engine of highest practicable compression ratio consistent with the degree of supercharging desired and the nondetonating quality of the fuel used because the power increase will be greater, the exhaust gas temperatures will be lower, and the power required by the supercharger to maintain the same pressure at the carburetor will be less.

INTRODUCTION

Increasing the engine power by increasing the compression ratio or by increasing the pressure at the carburetor has been the subject of several theoretical investigations. (References 1 and 2.) These investigations have led to the conclusion that considerably more power is developed, and the maximum cylinder pressures are much lower in a supercharged engine of low compression ratio than in an unsupercharged engine of high compression ratio. The results of the most comprehensive theoretical investigations have also shown that boosting when considered on an indicated-horsepower basis does not reduce the thermal efficiency.

Many experimental data are now available on the effect of compression ratio on engine performance, but very little experimental information is available regarding the effect of supercharging at different compression ratios. The lack of experimental information to verify the above-mentioned theoretical information and the present importance of any proposed method of improving aircraft-engine power caused the National Advisory Committee for Aeronautics to conduct these tests.

Performance data were obtained with compression ratios of 3.5, 4.5, 5.5, 6.5, and 7.5. At the three lower compression ratios, performance measurements were obtained for carburetor pressures varying from 30 to 42 inches of mercury absolute; at the 6.5 compression ratio measurements were obtained for carburetor pressures varying from 30 to 40 inches of mercury absolute; and at the 7.5 compression ratio measurements were obtained for carburetor pressures varying from 30 to 36 inches of mercury absolute. All runs were made at full throttle and at a constant engine speed of 1,500 revolutions per minute. In order to eliminate the effect of detonation, benzol was used as a fuel for all conditions.

APPARATUS AND METHOD

The N.A.C.A. single-cylinder universal test engine, described in Technical Report No. 250 (reference 3), was used for these tests. This engine, of 5-inch bore and 7-inch stroke, has two intake and two exhaust valves each 2¼ inches in diameter and is equipped with a Stromberg NA-L5-type carburetor. The engine has a variable compression volume, rendering it particularly suitable for these tests. The valve lift and timing can also be varied, but for these tests a lift of 0.3 inch and the standard Liberty valve timing were used. (Reference 4.) A special skeleton-type aluminum-alloy piston was employed for compression ratios from 4.5 to 7.5. This piston could not be used for the 3.5 compression ratio, because its skirt extended too far below the cylinder liner; therefore a standard Liberty engine piston was used for this ratio. The engine was directly connected to an electric dynamometer.

A Roots-type supercharger driven by an electric motor supplied carburetor air at the desired pressure. (Reference 5.) Two large surge tanks were interposed in the air duct between the engine and the supercharger: one, near the supercharger to dampen out the pressure pulsations from the supercharger; the other, close to the carburetor to prevent, as far as possible,

the effect of air pulsations from the engine. A photograph of the set-up of the equipment is shown in Figure 1, and a schematic drawing showing the arrangement of the equipment is shown in Figure 2.

In these tests, measurements were made of power, friction, fuel consumption, maximum cylinder pressures, carburetor-air temperatures and pressures, temperature and weight of the cooling water, and exhaust-gas temperatures.

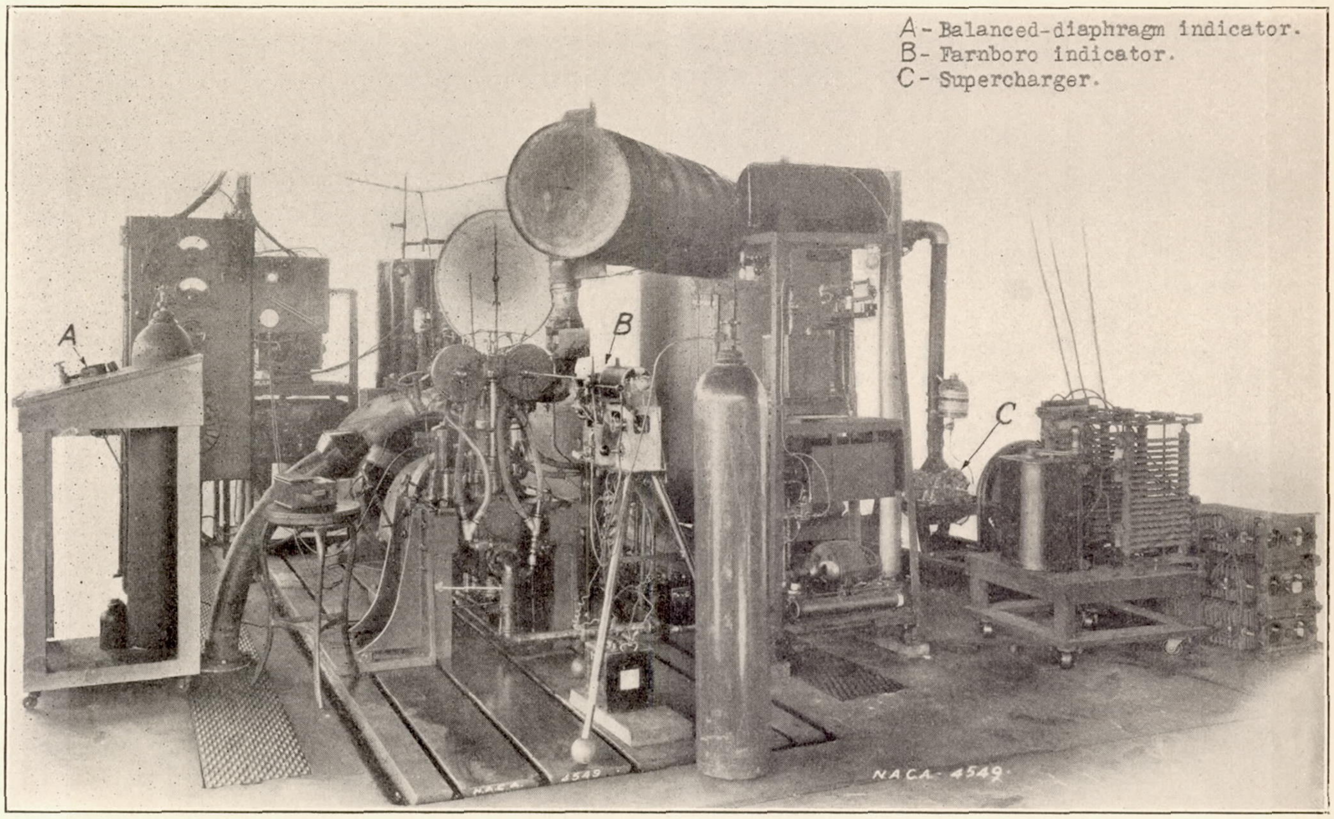

FIGURE 1.—Set-up of laboratory test equipment

The power developed and the friction losses were determined from the dynamometer scale readings and engine speeds. An electrically-controlled stop watch and two revolution counters were used to obtain the engine and the supercharger speeds.

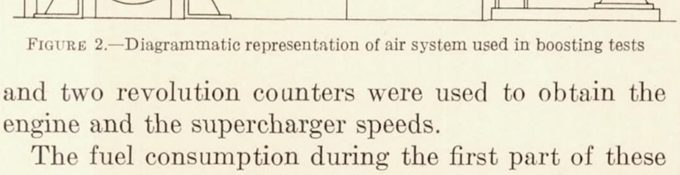

FIGURE 2.—Diagrammatic representation of air system used in boosting tests

The fuel consumption during the first part of these tests was determined from the time required to consume 0.5 pound of benzol. As the weighing method did not give very consistent results because the scales were not sensitive enough, it was replaced by the volume method, which gave satisfactory results. With the volume method, the time measured was that necessary for the engine to consume a volume of benzol weighing 481 grams at 80° F. To obtain consistent data that could be reproduced, the following method was used for two different carburetor pressures for each compression ratio. Three sets of readings were obtained: one with the mixture slightly richer than necessary, a second with approximately the correct mixture, and a third with the mixture lean enough to decrease the power slightly. From a plot of these data, the carburetor setting that gave the maximum power with a lean mixture was selected. No attempt was made to determine the fuel consumption at the most economical setting.

Maximum cylinder pressures were obtained as an indication of the mechanical stresses for each condition of operation. These pressures were arbitrarily limited to a maximum of 900 pounds. A balanced-diaphragm indicator (reference 6) was used for obtaining the pressure measurements. Indicator cards were taken with a Farnboro indicator. (Reference 7.) A photographic reproduction of a card from this indicator is shown in Figure 3.

A mercury manometer connected to the surge tank near the engine was used for measuring the carburetor pressures, and a mercury thermometer located in the

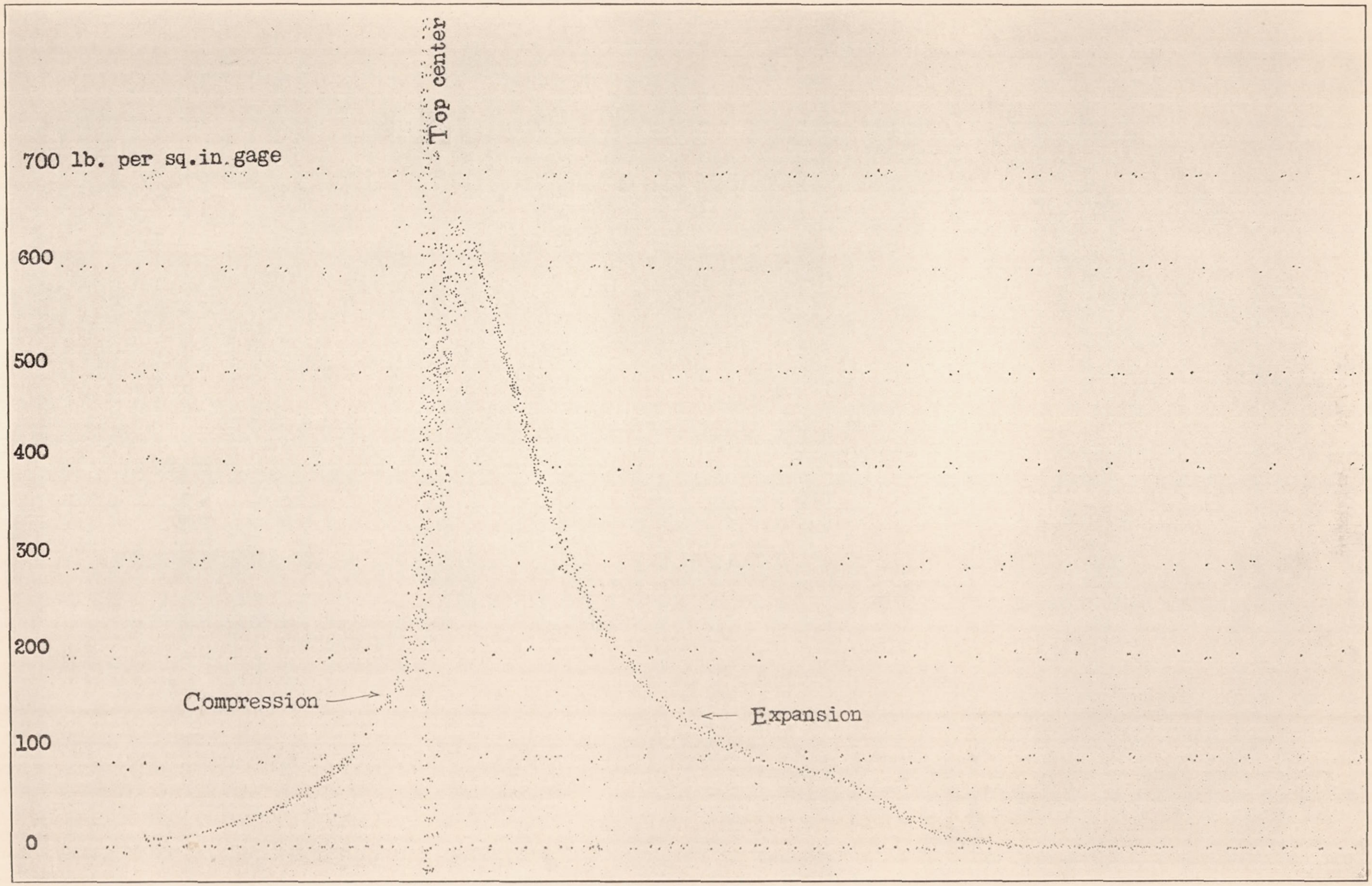

FIGURE 3.—Photographic reproduction of indicator card

carburetor-inlet stack was used for measuring the carburetor-air temperatures. In these tests the carburetor-air temperatures varied from 77° F. to 103° F., depending on the amount of boosting.

The heat losses to the cooling water were determined from measurements of the temperature of the cooling water going in and out of the cylinder head and barrel and the time required to circulate 50 pounds of water through each system. Mercury thermometers were used for measuring these temperatures.

The exhaust-gas temperature was measured to obtain an indication of the increase in valve temperatures and also to obtain an indication of the heat losses to the exhaust gases for each condition of operation. A base-metal thermocouple connected to a pyrometer was used for measuring the exhaust-gas temperatures. The thermocouple was made of 0.02-inch diameter wire; no attempt was made to provide it with shielding. It was located in the center of the 3-inch diameter exhaust stack about 4 inches from the exhaust valves.

The spark setting was adjusted for variation in compression ratio, but was not adjusted for variation in carburetor pressures, because several adjustments of the spark for changes in carburetor pressure gave no measureable improvement in performance. Since it is necessary to advance the spark setting to obtain optimum performance when the compression ratio is increased it is reasonable to assume that it should also be necessary when the carburetor pressure is increased, because of the resulting increase in compression pressure. If a large range of carburetor pressures had been investigated or if very careful measurements of the power at several different spark settings had been made for the maximum and the minimum carburetor pressures used in these tests, the spark setting for optimum power would probably have been discovered to be a few degrees earlier for the minimum carburetor pressures than for the maximum carburetor pressure. The in-going-water temperature varied from 142° F. to 155° F. and the outgoing-water temperature from 160° F. to 170° F. The outgoing-oil temperature varied from 135° F. to 145° F. The oil pressure was kept at about 50 pounds per square inch.

All engine power data obtained were corrected to a carburetor temperature of 59° F. In making this correction it was assumed that the brake horsepower varied inversely as the square root of the absolute temperature. This correction should be applied to the indicated horsepower; the error introduced in applying it to the brake horsepower was small, however, because the maximum variation in temperature from the standard was only 34° F. No attempt was made to apply a correction for humidity. The thermal efficiency was computed on the basis of 18,000 British thermal units per pound of benzol. Because the supercharger used in these tests was of much greater capacity than necessary, measurements of its power requirements were not made in determining the net engine power. Instead, the power required by a well-designed supercharger of suitable size for this service was computed from the thermodynamic relation

$$\text{Horsepower} = C\frac{n}{n-1}P_1V_1(r^{\frac{n-1}{n}}-1)$$

In this relation

P_1 is the supercharger intake pressure,
V_1 is the volume of intake air per second,
r is the pressure ratio,
C is a constant depending on the units used,
n is the compression exponent.

A supercharger adiabatic efficiency of 70 per cent was assumed. This assumption is supported by a large amount of experimental data. (References 5 and 8.)

RESULTS AND DISCUSSION

The power output of an internal-combustion engine depends on the amount of charge burned and the efficiency with which it is burned. As high thermal efficiency can be obtained by operating at a high compression ratio and a large quantity of mixture can be burned by using engines of large displacement or by using forced induction, it would seem that the problem of increasing the power output and the efficiency of an engine would be comparatively simple. Because the amount that the engine power can be increased by any of the foregoing methods is limited by the mechanical and the heat-resisting properties of the materials used, the problem of increasing the power output of an engine becomes difficult and involved.

The amount that the compression ratio can be increased is limited by the difficulty of obtaining nondetonating fuels in sufficient quantity to satisfy the demand. Furthermore, if the fuels were available, the high-explosion pressures obtained with the high compression ratios would be a limiting factor. These high pressures increase the stresses in the cylinders, bearings, crankcase, and reciprocating parts so that it is necessary either to increase the weight of these parts or to accept a reduction in engine reliability. The effect of compression ratio on the maximum cylinder pressures is shown by the indicator cards in Figure 4. Increasing the compression ratio from 3.5 to 7.5 resulted in an increase in b. m. e. p. of only 44.7 per cent, while the maximum cylinder pressures increased 130 per cent.

The amount that the displacement of an engine or the pressure at the carburetor of an engine can be increased without cooling or mechanical difficulties depends a great deal upon the ingenuity of the designer. His greatest difficulties would probably be with excessive cylinder-head, barrel, and valve temperatures on air-cooled engines. On water-cooled engines, he would probably be limited less by cooling difficulties and more by excessive weight of the reciprocating parts.

Increasing the displacement of an engine increases its frontal area and thus its drag. This is particularly true of radial air-cooled engines. The increase in drag is not serious, however, because the displacement would increase in a greater ratio than the drag. The

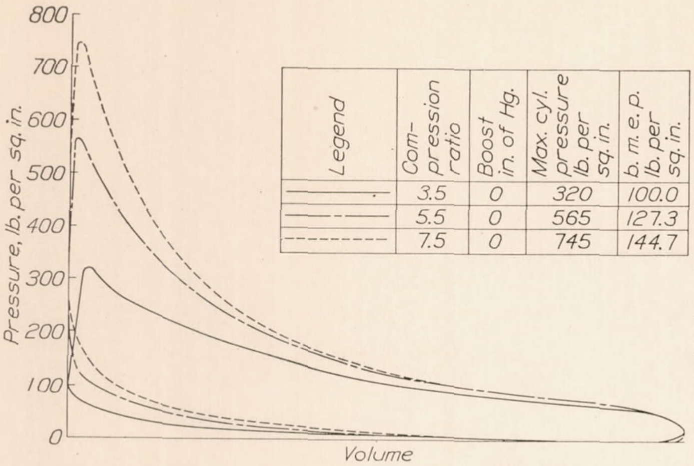

FIGURE 4.—Effect of increasing the compression ratio on maximum cylinder pressures and power

amount that the pressure at the carburetor can be increased would be limited at low compression ratios by cooling difficulties and at high compression ratios by the maximum cylinder pressures.

From the foregoing discussion it is evident that in order to use to advantage each or all of these methods for increasing the power output of an engine, the designer should know how each method affects the performance characteristics and the desirable qualities of the engine. So far we have mentioned only the power output as an important quality of an aircraft engine; there are others such as reliability, low-weight horsepower ratio, and economy, that must be carefully considered by the designer. To obtain these desirable qualities or as many of them as possible without impairing the remainder is a problem tha thas confronted engine manufacturers for the last decade.

Effect of boosting on power, fuel consumption, and maximum cylinder pressures.—The curves in Figures 5, 6, and 7 show the effect of boosting on power, on fuel consumption, and on maximum cylinder pressures, respectively. These curves show that boosting the carburetor pressure results in a large increase in power, a comparatively small increase in maximum cylinder pressures, and a slight decrease in fuel economy; whereas increasing the compression ratio results in a moderate increase in power, a large increase in maximum cylinder pressures, and a marked improvement in fuel economy. The values of b. m. e. p., fuel consumption, and maximum cylinder pressures in these figures are given in tabulated form in Table I so that their interrelation may be conveniently examined and studied.

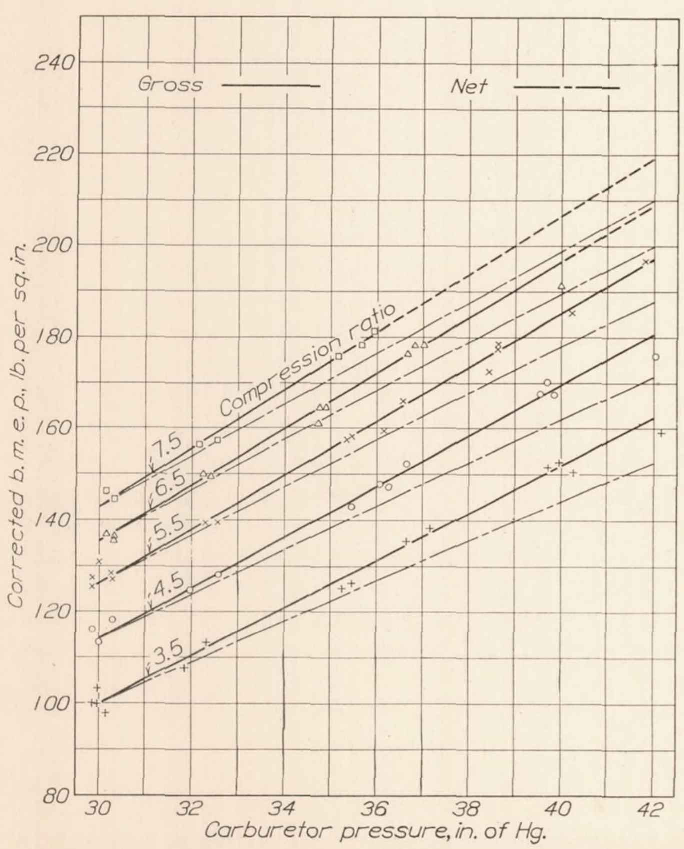

FIGURE 5.—Effect of boosting at different compression ratios on brake mean effective pressure

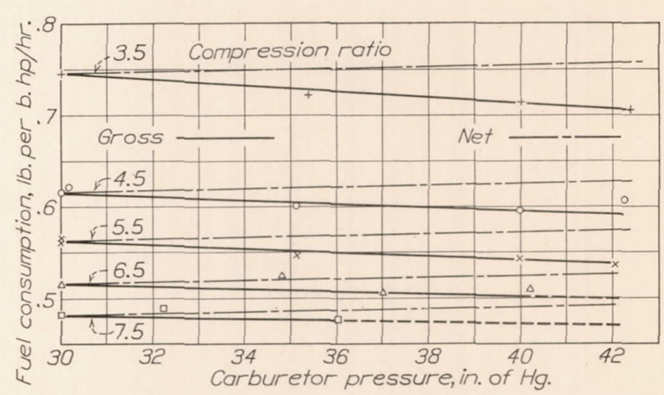

FIGURE 6.—Effect of boosting at different compression ratios on fuel consumption

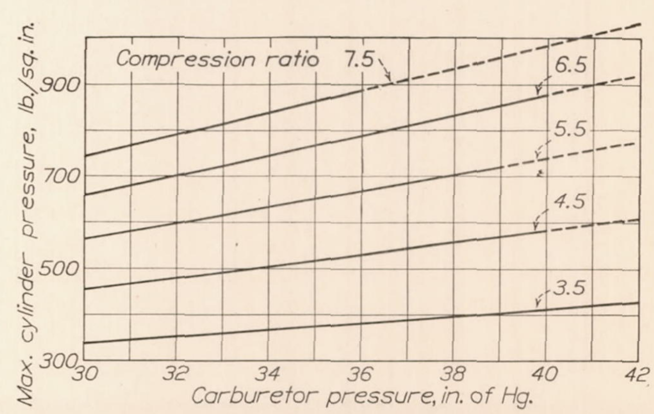

FIGURE 7.—Effect of boosting at different compression ratios on maximum cylinder pressures

TABLE I.—EFFECT OF BOOSTING CARBURETOR PRESSURES 10 INCHES OF MERCURY ON NET B. M. E. P., MAXIMUM CYLINDER PRESSURES, AND NET FUEL CONSUMPTION AS COMPARED WITH THE NORMAL ENGINE [1]

Compression ratio	B. m. e. p. lb./sq. in. no boost	B. m. e. p. lb./sq. in. 10 inches mercury boost	Increase in b. m. e. p. lb./sq. in.	Maximum cylinder pressure lb./sq. in. no boost	Maximum cylinder pressure lb./sq. in. 10 inches mercury boost	Increase in maximum cylinder pressure lb./sq. in.	Fuel lb./b. hp./hr. no boost	Fuel lb./b. hp./hr. 10 inches mercury boost
3.5	100.0	144.0	44.0	338	410	72	0.745	0.755
4.5	114.0	162.0	48.0	450	580	130	.615	.625
5.5	126.5	178.0	51.5	562	736	174	.560	.570
6.5	135.0	189.5	54.5	656	875	219	.515	.523
7.5	143.0	199.0	56.0	742	980	238	.480	.490

[1] This table has been reproduced from curves in Figures 5, 6, and 7.

These results indicate that there is no combination of compression ratio and carburetor pressure that is best for all conditions, but that a compromise must be made considering the purpose for which the engine is to be used. For instance, if high power output and reliability are more desirable than fuel economy, slightly lower compression ratios and higher carburetor pressures can be used; but if economy is the important consideration, higher compression ratios and lower carburetor pressures should be used. With a compression ratio of 5.5 and atmospheric pressure at the carburetor, the b. m. e. p. developed is 126.5 pounds and the maximum cylinder pressure 562 pounds; but, with a 4.5 compression ratio and 10-inch boost, the net b. m. e. p. is 162 pounds and the maximum cylinder pressure 580 pounds. There is very little difference in the mechanical stresses as indicated by these maximum pressures; the net specific fuel consumption has increased approximately 12 per cent and the net b. m. e. p. has increased approximately 30 per cent.

Assuming that the information obtained in these tests is applicable to conditions where the carburetor pressure ranges from 45 to 125 inches of mercury and applying the information to these conditions a b. m. e. p. of 750 pounds is obtained with a maximum cylinder pressure of 3,000 pounds at a compression ratio of 7.5. After subtracting the power required by the supercharger we have a net b. m. e. p. of 615 pounds. The ratio of the net b. m. e. p. to the maximum cylinder pressure would be lower than that for the normal engine. The net engine power would be increased more than four times, and the external dimensions would be the same except for the increased metal thickness necessary to withstand the high pressures.

Even if one should consider that the weight of the engine would increase directly with the increase in maximum cylinder pressures, the weight per horsepower would not be greater than that of a normal engine; but if one uses the more reasonable consideration that the weight would vary directly as the square root of the maximum cylinder pressures, then the weight would be considerably less for the supercharged engine. In the case considered above the power would be increased four times and the weight would be doubled. In addition the supercharged engine would have a much lower drag—a very important consideration if the speed of airplanes is to continue to increase.

In the design of such an engine the greatest difficulties would be in carrying away the waste heat from the cylinder walls and valves and in obtaining a satisfactory nondetonating fuel. The cylinder walls could probably be cooled by the use of an evaporative cooling system in which the cooling medium could be circulated at high velocities. Spiral fins could be used inside the water jacket to increase the area of metal in contact with the coolant and to give strength to the cylinder. The use of a high-temperature-evaporative system for cooling would permit the use of small radiators, so that little, if any, of the reduction in engine drag would be sacrificed on account of the increase in size of the radiator.

If poppet valves are used, means must be provided for cooling the valves. This cooling probably could be satisfactorily accomplished by providing air ducts from the supercharger to the valves so that compressed air could be forced through the valves. For this service a sleeve-valve motor would be more satisfactory, because no difficulty would be experienced in cooling the valves and because the higher pressures at the end of the stroke would not increase the load on the valve gears. The exhaust ports of such an engine would also have to be larger so that the gases could escape from the cylinder sufficiently early to prevent an appreciable increase in pressure on the scavenging stroke.

To justify the use of superchargers, except for special conditions where a large power reserve is the important consideration; the weight-horsepower ratio and the drag of the engine should be lower when supercharged than when unsupercharged. In some cases, the reduction in drag on multiengine airplanes may be large, because it may be possible to reduce the number of engines that are used. To reduce the weight-horsepower ratio of an unsupercharged engine at altitude by supercharging or boosting is not difficult. At altitudes from 15,000 to 20,000 feet a reduction of 1.5 to 2 pounds per horsepower is possible on an engine

developing 400 horsepower at sea level. The reduction in weight per horsepower would be larger for a smaller-sized engine.

To reduce, by boosting, the weight-horsepower ratio of an engine operating near sea level or at very low altitudes is difficult unless a large amount of boosting is used. The weight-horsepower ratio of an engine developing 400 horsepower unsupercharged may be reduced from one-half to three-fourths pound per horsepower by boosting the carburetor pressure 10 inches of mercury. However, when the specific weight of the supercharged engine for the above condition is compared with that of an unsupercharged engine of the same power output, the difference in weight is negligible. There are special cases, however, where the use of a supercharger is justified even though there is no reduction in specific weight. In such cases the supercharger corresponds, in a practical sense, to an extension on the throttle, because the amount of mixture taken in can be increased by increasing the pressure at the carburetor. This case could be used advantageously to aid in the take-off of heavily loaded airplanes or to improve the speed or climb performance of scouting airplanes operating at low altitudes.

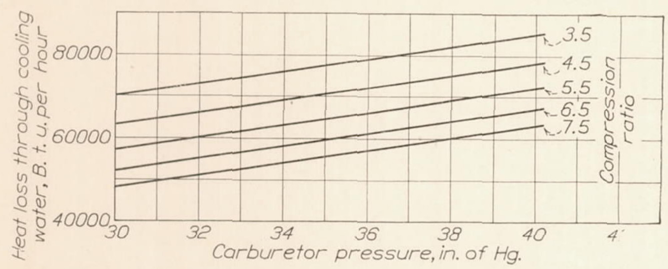

FIGURE 8.—Effect of boosting at different compression ratios on the heat losses to the cooling water

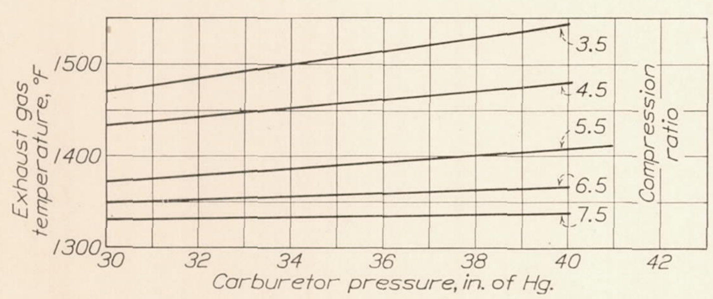

FIGURE 10.—Effect of boosting at different compression ratios on exhaust-gas temperatures

Although it is not the purpose of this report to compare from the commercial operator's point of view the high-compression engine with that of the supercharged medium-compression engine, a few computations were made to determine which engine is the most economical to operate. These computations were based on many assumptions, on the meager data available on operating costs, on the little information available regarding reliability, life, and cost of upkeep of the two kinds of engines, and on the experimental data presented in this report on fuel consumption and power. The results of these computations show that for low and moderate altitudes the high-compression engine is most economical. For operating at high altitudes, about 25,000 feet, the supercharged medium-compression engine is more economical than the normal high-compression engine, but even for these favorable conditions it is questionable whether it would be equal to the high-compression engine operating at low altitudes.

Heat losses to the cooling water and exhaust gasses.—Increasing the weight of mixture burned by increasing the pressure at the carburetor results in a larger quantity of heat being liberated; consequently, a greater quantity of heat units must be carried off by the cooling water. The results for these tests, as shown by the curves in Figure 8, indicate that the quantity of heat

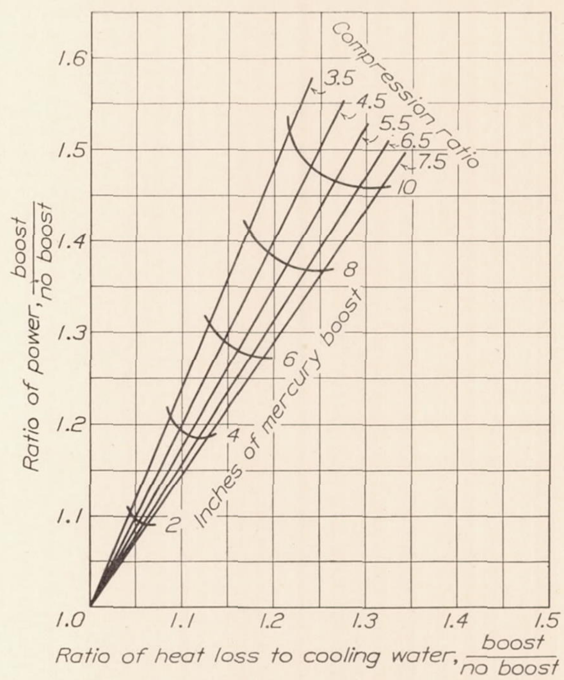

FIGURE 9.—Ratio of power to ratio of heat losses to cooling water with different degrees of boosting at different compression ratios

that would be carried away by the cooling water increases directly with the carburetor pressure for each compression ratio and that the heat losses to the cooling water decrease considerably with an increase in compression ratio. It follows that the increase in radiator area will be the same for a given amount of boost regardless of the compression ratio. However, the percentage increase in radiator area will be higher for the high compression ratio, because the size of radiator used on a normal high-compression engine would be smaller than that used on a normal low-compression engine. The curves in Figure 9 show the percentage increase in radiator area necessary, at each compression ratio, for various amounts of boosting. Increasing the horsepower of an engine of 3.5 compression ratio 50 per cent by supercharging results in a 20 per cent in-

crease in losses to the cooling water; increasing the horsepower of an engine of 7.5 compression ratio 50 per cent by supercharging results in an increase of 34 per cent in losses to the cooling water.

The curves in Figure 10 show the effect of boosting the carburetor pressure on the exhaust-gas temperature. It is interesting to note that boosting at high compression ratios has very little effect on the exhaust-gas temperatures, whereas boosting at low compression ratios results in a definite increase in the exhaust-gas temperature. The advantage of supercharging an engine of high compression ratio is apparent when one considers that the intensity of the heat is more detrimental to engine reliability than the quantity of heat. Considering the high exhaust-gas temperatures, the low power, and the high fuel consumption one can safely say that the supercharging of engines of very low compression ratio is impracticable. To obtain good performance by boosting the compression ratio used should not be less than 4.5.

Mechanical efficiency and f. m. e. p.—As the f. m. e. p. and mechanical efficiency are more or less related they will be discussed together. The curves in Figure 11 show that boosting the carburetor pressure 10 inches of mercury results in an increase in gross mechanical efficiency of about 5 per cent at the high compression ratios and about 7 per cent at the low compression ratios. This increase in mechanical efficiency is caused by reduced pumping losses and increased power output. The gross mechanical efficiency represents conditions when the power required to drive the supercharger is not considered. The net mechanical efficiency curves represent conditions when the supercharger is driven directly by the engine. Note that the difference between the gross and net mechanical efficiency decreases with an increase in compression ratio and that the optimum net mechanical efficiency is reached at a lower carburetor pressure on a low-compression engine than on a high-compression engine. The effect of boosting on f. m. e. p. is shown by the curves in Figure 12. The reduction in friction is caused by higher pressures on the piston during the intake stroke. A lower friction was obtained with the 3.5 compression ratio, because a different piston was used.

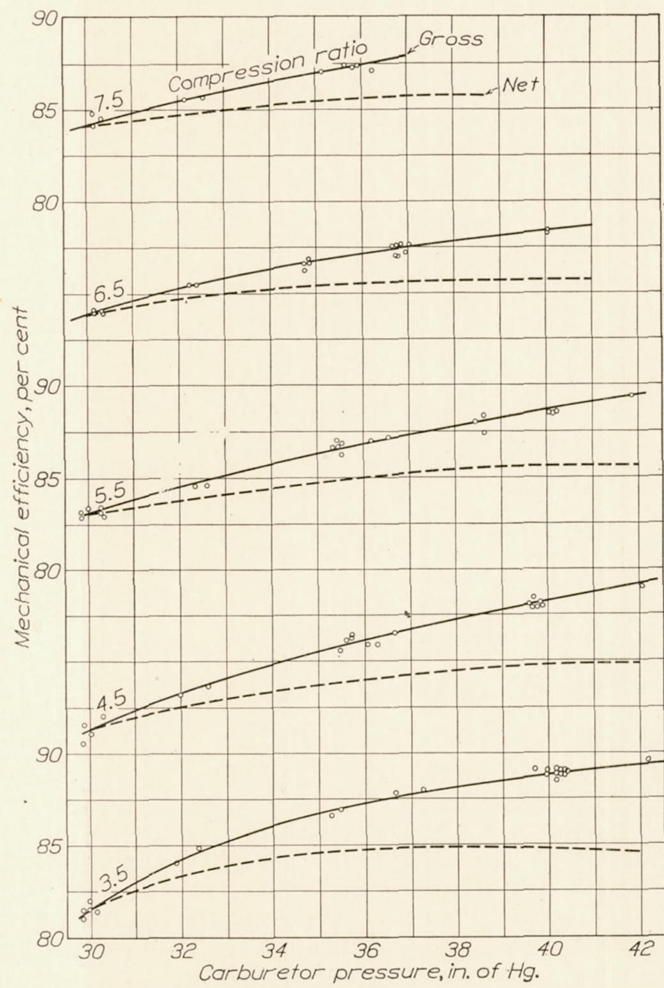

FIGURE 11.—Effect of boosting at different compression ratios on mechanical efficiency

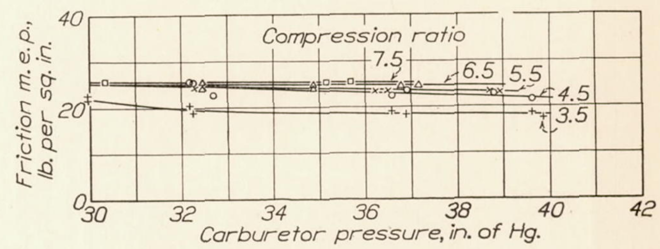

FIGURE 12.—Effect of boosting at different compression ratios on the friction m. e. p.

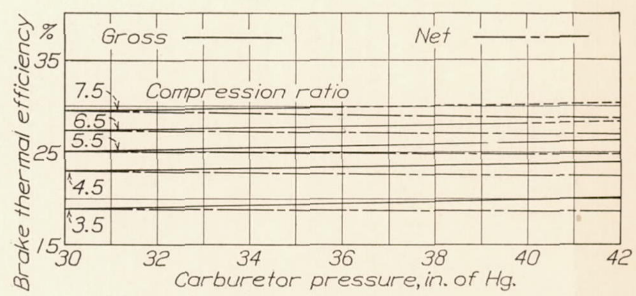

FIGURE 13.—Effect of boosting at different compression ratios on brake thermal efficiency

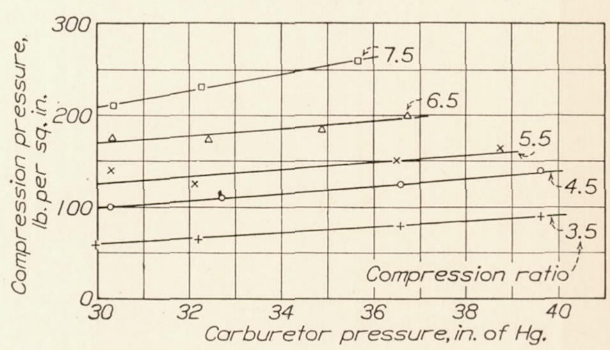

FIGURE 14.—Effect of boosting at different compression ratios on the compression pressures

Thermal efficiency.—The total compression ratio of a supercharged engine is equal to the product of the compression ratio of the supercharger and of the engine. Many investigators are of the opinion that the thermal efficiency of a supercharged engine is lower than that of an unsupercharged, because its expansion ratio is not equal to the total compression ratio. This does not seem reasonable, because the efficiency of an engine depends on the expansion ratio and not on the total compression ratio. As the expansion ratio remains the same, it is reasonable to expect that the thermal efficiency of a boosted engine should be affected only to the extent that boosting effects the combustion efficiency and net mechanical efficiency. The curves in Figure 13 show that boosting results in only a slight decrease in net thermal efficiency.

Compression pressures.—The compression pressure obtained for each compression ratio with different degrees of boosting is shown by the curves in Figure 14. The measurements were obtained with the balanced-diaphragm indicator with the engine motoring at a speed of 1,500 revolutions per minute.

Indicator cards.—The indicator cards in Figure 15 show the effect of supercharging at different compression ratios on the pressures at various points in the cycle. These cards are valuable because they help visualize what takes place within the cylinder. They also show the high pressures at the end of the stroke against which the valve must open when a high degree of boosting is used. The b. m. e. p. and the maximum cylinder pressure values given on the cards correspond to those obtained during the run when the card was taken.

CONCLUSIONS

1. Boosting the carburetor pressure 10 inches of mercury results in a net increase of 44 b. m. e. p. for an engine of 3.5 compression ratio and a net increase of 56 b. m. e. p. for an engine of 7.5 compression ratio; these results indicate the desirability of boosting an engine of the highest practicable compression ratio consistent with the degree of supercharging desired and the nondetonating quality of the fuel used.

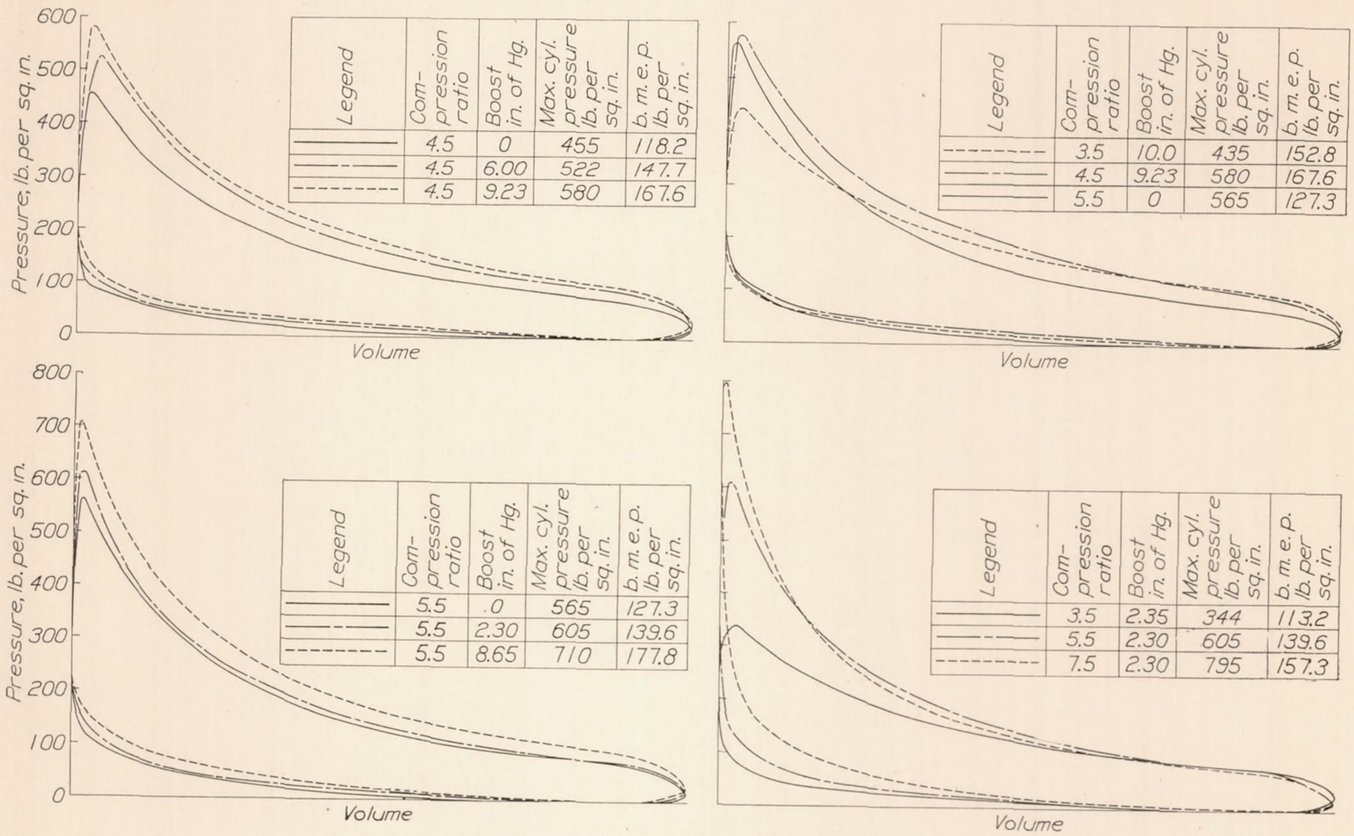

FIGURE 15.—Pressure-volume diagrams for several operating conditions

2. A large increase in net engine power can be obtained by boosting at medium compression ratio with very little increase in maximum cylinder pressure and with only a small increase in fuel consumption, as compared with operating normally at slightly higher compression ratios.

3. Within the limits of these tests the decrease in thermal efficiency with boosting is negligible.

4. Boosting results in a percentage increase in power that is larger than the percentage increase in losses to the cooling water. Increasing the power 50 per cent increases the loss to the cooling water 20 per cent at a compression ratio of 3.5, while increasing the power 50 per cent increases the loss to the cooling water 34 per

cent at a compression ratio of 7.5. In each case the actual increase in heat loss was the same.

5. Boosting the carburetor pressure 10 inches of mercury increases the exhaust-gas temperatures about 75° F. at a compression ratio of 3.5, but at a compression ratio of 7.5 the increase is only about 10° F.

6. Boosting the carburetor pressure 10 inches of mercury increases the mechanical efficiency approximately 5 per cent for the high compression ratios and 7 per cent for the low compression ratios.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *May 29, 1931.*

REFERENCES AND BIBLIOGRAPHY

1. Funck, Georges: The Supercharging of Internal Combustion Engines. Automobile Engineer, Oct., Nov., Dec., 1919.
2. Fedden, A. H. R.: The Supercharging of Aircraft and Motor-Vehicle Engines. Roy. Aero. Soc. Jour., Oct., 1927, Vol. XXXI, No. 202, pp. 933–961.
3. Ware, Marsden: Description of the N. A. C. A. Universal Test Engine and Some Test Results. N. A. C. A. Technical Report No. 250, 1927.
4. Schey, Oscar W., and Biermann, Arnold E.: The Effect of Valve Timing Upon the Performance of a Supercharged Engine at Altitude and an Unsupercharged Engine at Sea Level. N. A. C. A. Technical Report No. 390, 1931.
5. Ware, Marsden: Description and Laboratory Tests of a Roots Type Aircraft Engine Supercharger. N. A. C. A. Technical Report No. 230, 1927.
6. Spanogle, J. A., and Collins, John H., jr.: A Balanced Diaphragm Type of Maximum Cylinder Pressure Indicator. N. A. C. A. Technical Note No. 359, 1930.
7. Collins, John H., jr.: Alterations and Tests of the "Farnboro" Engine Indicator. N. A. C. A. Technical Note No. 348, 1930.
8. Chenoweth, Opie: Supercharged Engine Performance, Calculated and Actual. S. A. E. Jour., Nov., 1927, Vol. XXI, No. 5, pp. 508–515.

Cameron, J. G.: Supercharging. A Statement of the Fundamental Principles. Automobile Engineer, Aug., 1925, Vol. XV, No. 205, pp. 244–247.

Taylor, C. Fayette, and Porter, L. Morgan: Some Aspects of Supercharging for Sea-Level Conditions. S. A. E. Jour., Feb., 1928, Vol. XXII, No. 2, p. 195–199.

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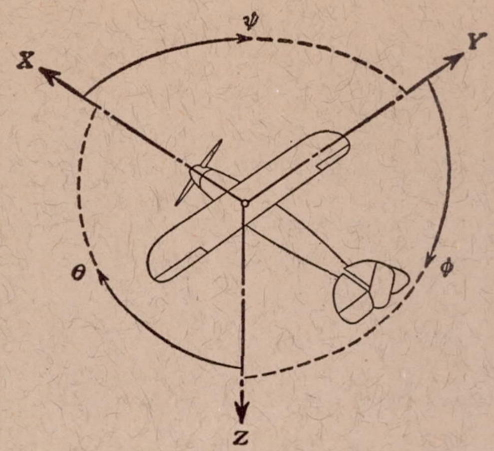

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	ϕ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p, Geometric pitch.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slipstream velocity.
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$.
C_S, Speed power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$.
η, Efficiency.
n, Revolutions per second, r. p. s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.